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Multi Units of Three Phase Photovoltaic using Band Pass Filter to Enhance Power Quality in Distribution Network under Variable Temperature and Solar Irradiance Level

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ABSTRACT

The paper proposed power quality enhancement on three phase grid of point common coupling (PCC) bus due to integration of multi units of photovoltaic (PV) to 380 volt (phase-phase) 50 Hz low voltage distribution network under variable temperature and irradiance level. The band pass filter models (single tuned and double tuned) were installed to improvement power quality on the conditions i.e. without filter, with single tuned filter, and with double tuned filter. Multi units of PV generator without filter, with single tuned, and with double tuned filter at all temperatures and irradiance levels resulted in relatively stable phase voltage (308 and 310 volt), so able to generate an unbalanced voltage of 0%. The maximum phase current for the system without filter at all temperatures and radiation levels of 9.8, 12.5, and 10 ampere respectively, resulted in an unbalanced current of 16.10% . Under the same condition, single tuned and double tuned filters were able to balance phase current to 10.45 A and 10.44 ampere respectively, resulting in an unbalanced current of 0%. Implementation of single tuned and double tuned filters was able to reduce unbalance current according to ANSI/IEEE 241-1990. At constant temperature and irradiance increased, both average voltage and current harmonics also increased. Double tuned active filter was the most effective to suppress the 11th and 13th harmonics so that capable to migitate average voltage and current harmonics better than system using single tuned filter which could only reduce 5th harmonic within IEEE 519-1992.

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1. INTRODUCTION

The PV beside being able to generate power, it also results harmonics due to inverter as a medium to convert DC into AC voltage so can decrease power quality. Randomly installed PV generators in low voltage distribution network (grid) are also able to deliver unbalanced line current. This renewable energy based DGs also has intermittent characteristics and produces power depend on environmental condition i.e. temperature and solar irradiation level. The research on power quality of PV generator connected grid to power system using LCL filter has been done Kon Keng Weng et. al. A number of power quality problems i.e. over voltage, less voltage, power fluctuations, inrush currents, low power factor, and current harmonics or total harmonics distortion (THD) will appear on microgrid power systems. This research is conducted only on constant solar irradiance and temperature condition (1000 W/m^2 and 25^0 C) as environmental input parameters for PV systems [1]. The study on effect of solar radiation on grid connected to PV generator to power quality i.e.

voltage/current hamonics, active/reactive power, and power factor correction has been investigated by Minas Patsalides, et.al. It considers two different scenarios of average and low radiation. The shortcoming is not to consider effect of temperature as an input variable for PV generator [2]. Investigation of grid connected a single phase PV generator inverter using a current proportional resonant, proportional resonant integral, and genetic algorithm using an active filter to reduce current harmonics of inverter output has been studied by Renu et. al. The laxity of research is only done on a single phase system as well as certain solar irradiantion and temperature [3].

The dynamic analysis of power quality due to high penetration effect of distribution network connected to PV system under variable solar irradiance has been studied by Massoud Farhoodnea, et. al. It was performed on a 16 bus system model and the result showed that high level penetration of grid connected PV will cause a number of power quality problems i.e. swell/flicker voltage, loss power factor and current harmonics. The system is only analyzed on voltage harmonics and did not consider the ambient temperature condition [4]. Power quality characteristics in a number of three phase PV inverters at top roof PV i.e. harmonics distortion, voltage fluctuation, reactive power and power factor have been performed by K.P. Kontogianis, et. al [5]. The investigation of a three phase grid connected to a PV generator using maximum power point tracking (MPPT) with perturb and observe (P and O) algorithm and voltage source inverter controller, as well as its effect on current harmonics injected into the grid and a grid voltage harmonic has been investigated by Almas Hossain Mollah et.al.The research are only carried out at single irradiance and temperature (1000 W/m^2 and 25 ^{o}C) and did not consider voltage/current harmonics migitation according to IEEE 519-1992 [6]. The effect of PV generator integration on power quality on three phase grid PCC bus under variable solar irradiance using double tuned filters has been studied by Amirullah et. al. The results shows that at a fixed solar radiation level, the more a number of PV generators connected to three phase grid, average THD of grid voltage/current increased. Otherwise at level of solar irradiace increased, average THD of grid voltage/current also increased. Double tuned passive filter can reduce average THD of grid voltage/current. However, the research is carried out at a fixed temperature level of 40^{0}C, whereas the fact indicates that ambient temperature and solar irradiance are the main input variable for PV generator whose values are always changing with time [7]. A combined system of a three-phase four-wire shunt active power filter (SAPF), and photovoltaic generator (PVG) have been proposed by Richid Belaidi, et.al. The PVG-SAPF is capable to solve the power quality problems such as reduce harmonic current, compensate reactive power for power factor correction, and unbalance load, as well as inject the issued energy from the PVG into the utility grid. However, the power quality parameter analysis in this paper was only performed by using single PVG [8]. The method for balancing line current and voltage, due to the presence of DGs i.e. a number of single phase PV generation units in homes has been presented by Amirullah, et.al. The single phase PV generator is installed randomly on a 220 kV and 50 Hz three phase four wire distribution network using battery energy storage (BES) and three single phase bidirectional inverter circuits. The result shows that the combination of BES and three single phase bidirectional inverter are able to reduce unbalanced line current/voltage. Otherwise, the combination of both circuit is able to inreases current/voltage harmonics [9].

This paper presents enhancement of power quality performance due to integration of multi units PV generator using a band pass filter to 380 kV (phase-phase) 50 Hz low frequency distribution network on PCC bus under variable temperature and solar irradiance level. The model is composed of three PV generators group with 100 kW active power. Beside connect to three phase grid, PV generators are also linked to three groups of three phase loads each having 20 kW active power. Power quality studied are voltage and current unbalance as well as voltage and current harmonics in 12 scenarios on PV generator connected PCC bus of three phase grid. The band pass filter models (single tuned and double tuned) are installed to enhance power quality on the conditions i.e. without filter, with single tuned filter, and with double tuned filter. The results are further validated with ANSI/IEEE 241-1990 (voltage and current unbalance) and IEEE 519-1992 for (voltage and current THD), as a base to determine power quality level. Simulation and analysis results use Matlab/Simulink environment.

The rest of paper is organized as follow. Section 2 presents research method i.e. proposed model of single PV generator with band pass filter, model multi units of PV generator, simulation parameters, equivalent circuit and mathematical of PV model, harmonics and voltage/current unbalance, and band pass filter model. Section 3 describes influence of variable solar irradiance and temperature level of three model PV generator to voltage and current unbalance as well as voltage and current THD ,without filter, with single tuned filter, and double tuned filter. In this section, example cases studied are presented and its results are verified with those of Matlab/Simulink. Finally, the paper in concluded in Section 4.

2. RESEARCH METHOD

2.1. Proposed Method

The model of a single 100 kW PV generator connected to a three phase grid is shown in Figure 1. The PV system produces output voltage become as input for the DC/DC converter. The MPPT with P and O algorithm helps single phase PV generator resulting maximum power. The low DC output voltage from PV generator is increased by DC/DC boost converter to produce output voltage by adjusting duty cycle by switching device. The DC output is further converted by a three phase DC/AC inverter circuit to an AC voltage to a three phase grid using six insulated gate bipolar transistors (IGBTs) circuit base on pulse width modulation (PWM). Figure 2 shows proposed model of three groups of PV generator linked to a 380 volt (phase-phase), 50 Hz three phase low voltage distribution network on PCC bus and a 100 MVA, 20 kV three phase grid through a 100 kVA, 20 kV/380 V three phase power transformer.

This paper performs power quality enhancement on three phase grid of PCC bus due to integration of PV generator to 220 kV 50 Hz low voltage distribution network under variable temperature and irradiance level. The research uses three group models PV generator each with 100 kW active power. The power quality parameters are voltage and current unbalance, as well as voltage and current harmonics in 12 PV generator scenarios PV connected distribution network on PCC bus. The first scenario is without filter at the irradiance level i.e. 400 W/m^2, 600 W/m^2, 800 W/m^2, and 1000 W/m^2. The second and third scenarios are with single tuned filter and double tuned filter at the same irradiance level respectively. The temperature degree of each condition are 20^0, 25^0, 30^0, 35^0, and 40^0 Celcius. So that the total scenarios are 12 different irradiantion levels (without filter, with single tuned filter, and with double tuned filter) where it has five temperatures degree.

The simulation is performed to determine voltage and current waveform of a three phase distribution network on PCC bus. The band pass filter model i.e. single tuned and double tuned is used to improve power quality performance. The single tuned filter serves to suppress 5th single harmonic while double tuned filter expected to reduce 11th and 13th harmonics. A three phase phase circuit breaker (CB) is used to connect and disconnect band pass filter between a single PV generator and a three phase grid. The next process is to determine unbalance voltage and current as well as voltage and current THD in each scenario. Its results are further validated with ANSI/IEEE 241-1990 (unbalance voltage and current) and IEEE 519-1992 (voltage and current THD) as the basis for determining power quality level. Simulation and analysis of research results use Matlab/Simulink.

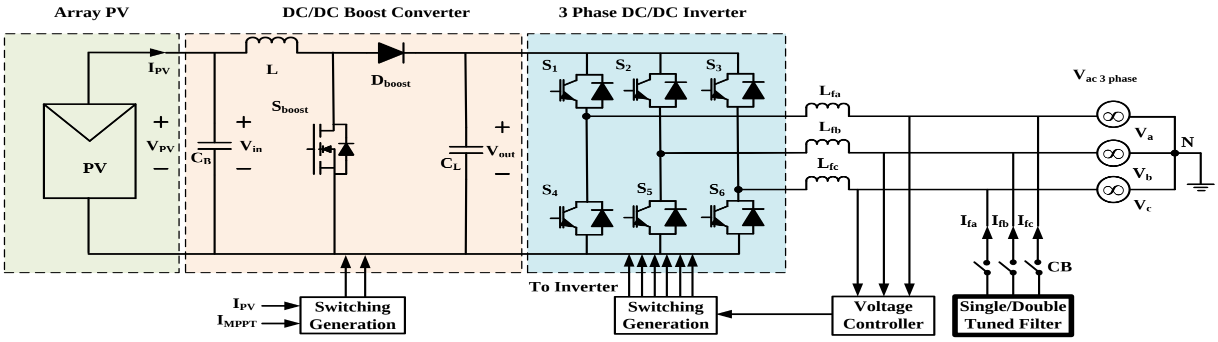


Figure 1. Model of single PV generator connected three phase grid with band pass filter

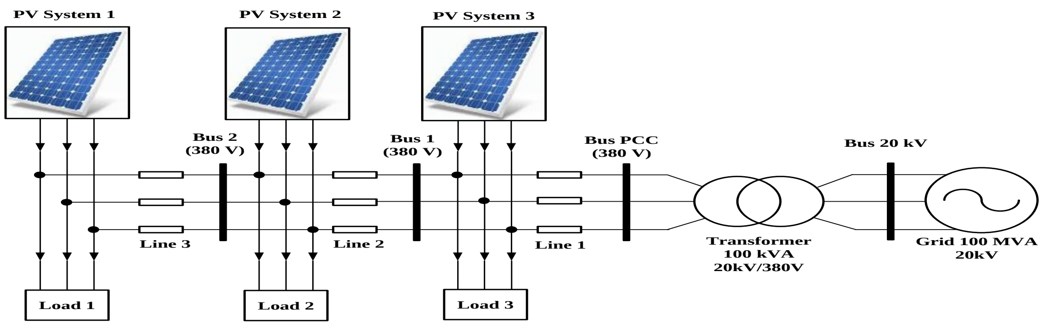


Figure 2. Proposed model of multi units of PV generator connected to three phase grid

Table 1 shows the devices, parameters, and simulation values of proposed model.

Table 1. Simulation Parameters

No.	Devices	Parameters	Values
1.	PV Generator 1, 2, and 3	Active Power	100 kW
		Temperature	20^0, 25^0, 30^0, 35^0, and 40^0 C
		Irradiance	400, 600, 800, and 1000 W/m^2
2.	Three Phase Grid	Short Circuit MVA	100 MVA
		Voltage (phase-phase)	380 volt
		Frequency	50 Hz
3.	Power Transformer	Power	100 kVA
		Frequency	50 Hz
		Voltage	380 Volt/20 kV
4.	Load 1, 2, and 3	Active Power	20 kW
		Voltage	380 Volt
		Frequency	50 Hz
5.	Low Voltage Line 1,2, and 3	Resistance	R = 0,1273 Ohm/km
		Inductance	L = 93,37 mH/km
		Capacitance	C = 1,274 μF/km
6.	Length of Low Voltage Line 1,2, and 3	Line 1	1 km
		Line 2	1 km
		Line 3	1 km
7.	DC Link Capasitor	Capacitance	2000 μF
8.	PWM Generator on Each PV	Frequency	4 kHz
		Sampling time	5 x 10^{-6} detik
9.	Single Tuned Filter	Reactive Power	50 MVAR
		Voltage (phase-phase)	380 V
		Frequency System	50 Hz
		Frequency Tuning	f = 5 x 50 Hz
		Quality Factor (Q)	16
10.	Double Tuned Filter	Reactive Power	50 MVAR
		Voltage (phase-phase)	380 V
		Frequency System	50 Hz
		Frequency Tuning	f_1 = 11 x 50 Hz, f_2 = 13 x 50 Hz
		Quality Factor (Q)	16

2.1. Photovoltaic Model

Figure 3 shows the equivalent circuit of a solar panel. A solar panel is composed of several PV cells that have series, parallel, or series-parallel external connections [10].

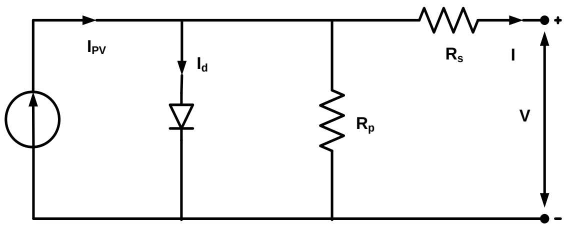


Figure 3. Equivalent circuit of solar panel

The V-I characteristic of a solar panel is showed in (1):

$$I = I_{PV} - I_o\left[\exp\left(\frac{V + R_S I}{aV_t}\right) - 1\right] - \frac{V + R_S I}{R_P} \tag{1}$$

where I_{PV} is the photovoltaic current, I_o is saturated reverse current, 'a' is the ideal diode constant, $V_t = N_S K T q^{-1}$ is the thermal voltage, N_S is the number of series cells, q is the electron charge, K is the Boltzmann constant, T is the temperature of p–n junction, R_S and R_P are series and parallel equivalent resistance of the solar panels. I_{PV} has a linear relation with light intensity and also varies with temperature variations. I_o is dependent on temperature variations. The values of I_{pv} and I_o are calculated as following (2) and (3):

$$I_{PV} = (I_{PV,n} + K_1 \Delta T) \frac{G}{G_n} I \tag{2}$$

$$I_o = \frac{I_{SC,n} + K_I \Delta T}{\exp(V_{OC,n} + K_V \Delta T) / aV_t - 1} \tag{3}$$

In which $I_{PV,n}$, $I_{SC,n}$ and $V_{OC,n}$ are photovoltaic current, short circuit current and open circuit voltage in standard conditions (T_n = 25 C and G_n = 1000 Wm^{-2}) respectively. K_I is the coefficient of short circuit current to temperature, $\Delta T = T - T_n$ is the temperature deviation from standard temperature, G is the light intensity and K_V is the ratio coefficient of open circuit voltage to temperature. Open circuit voltage, short circuit current and voltage-current corresponding to the maximum power are three important points of I-V characteristic of solar panel. These points are changed by variations of atmospheric conditions. By using (4) and (5) which are derived from PV model equations, short circuit current and open circuit voltage can be calculated in different atmospheric conditions.

$$I_{SC} = (I_{SC} + K_1 \Delta T) \frac{G}{G_n} \tag{4}$$

$$V_{OC} = V_{OC} + K_V \Delta T \tag{5}$$

2.2. Voltage/Current and Unbalance Harmonics

Power quality means quality of voltage and current. Power quality is determined based on the voltage and current value or the tolerance limit of equipment used. In general, current and voltage wave form of pure sinusoidal waves. One problem that occurs is non sinusoida or distorted current and voltage waves generated by harmonics in the power system [11]. Harmonic is distorted periodic steady state wave caused by the interaction between the shape of a sine wave at the fundamental frequency system with another wave component which is an integer multiples frequency of fundamental frequency. The most common harmonic index, which relates to the voltage waveform, is THD, which is defined as the root mean square (rms) of the harmonics expressed as a percentage of the fundamental component as showed in (12). For most applications, it is sufficient to consider the harmonic range from the 2nd to 25th, but most standards specify up to the 50th. Second harmonic index is current THD means the ratio of rms harmonic current value to rms fundamental current which expressed in (7) [11].

$$THD_V = \frac{\sqrt{\sum_{n=2}^{N} V_n^2}}{V_1} \times 100\ \% \tag{6}$$

$$THD_I = \frac{\sqrt{\sum_{n=2}^{N} I_n^2}}{I_1} \times 100\ \% \tag{7}$$

Where V_n and I_n (the rms voltage and current at harmonic n), V_1 and I_1 (the fundamental rms voltage and current), N (the maximum harmonic order to be considered). The allowable maximum THD value for each country is different depending on the standard used. THD standards most often used in electric power system is IEEE 519-1992. There are two criteria used in the analysis of harmonic distortion that voltage distortion limit and current distortion limit [13].

There are several standards that can be used to determine level of voltage unbalance in three phase systems, e.g. IEC, NEMA, and IEEE. In this study, value of unbalance voltage use Equation 8 is based ANSI/IEEE 241-1990 Standard [14] as follows:

$$V(\%) = \frac{\left| V_{a\,\text{varage}} - V_{a,b,c\,\min\,or\,\max} \right|}{V_{a\,\text{varage}}} \times 100\% \tag{8}$$

By using Equation (8), value of unbalance voltage expressed in percent (%) and is defined as follows; $V_{avarage}$ is the average value of maximum voltage on phase a, b, c, (volt), $V_{a,b,c\ min}$ is minimum voltage on phase a, b, c, (volt), $V_{a,b,c\ max}$ is maximum voltage on phase a, b, c (volt). By using the same equation, then percentage of unbalance current can be calculated by replacing voltage magnitude into current magnitude.

2.3. Band Pass Filter

The shunt passive filters always considered as good solution to solve harmonics current problems. Shunt passive filters can be classified into three basic catagories as follows (a) Band pass filters (of single or double tuned), (b) High pass filters (of first, second, third-order or C-type), and (c) Composite filters as shown in Figure 4 [7]. There are two models of band pass filter, i.e. single tuned filter and double tuned filter. A single tuned filter consisting of inductor L, capacitor C and small damping resistor R are connected in parallel with non-linear loads to provide low impedance paths for specific harmonic frequencies, thus resulting in absorbing the dominant harmonic currents flowing out of the load. Furthermore it also compensates reactive power at system operating frequency [15]. Single tuned passive filters are used to suppress harmonic at a single frequency e.g. 5^{th}, 7^{th}, 9^{th}, 11^{th}, or 13^{th} harmonic. Whereas double tuned passive filter is used to eliminate harmonics at two frequencies such as the 5^{th} and 7^{th} harmonics or the 11^{th} and 13^{th} harmonics [16]. In this paper a single tuned filter and double tuned filter model are used to reduce 5^{th} harmonics as well as 11^{th} and 13^{th} harmonics respectively.

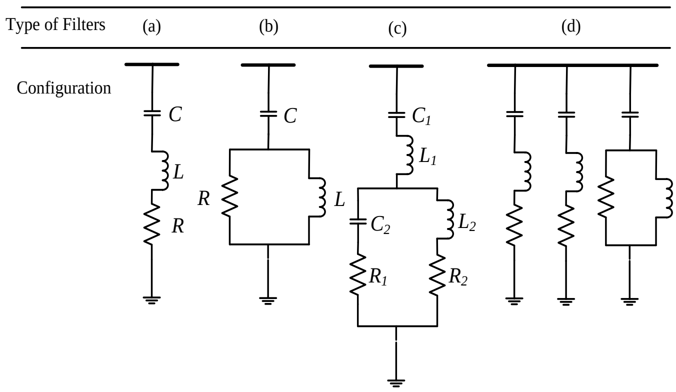


Figure 4. Models of passive filters: (a) band pass, (b) high pass, (c) double band pass, (d) composite

3. RESULTS AND ANALYSIS

The results analysis is began from determination of maximum and minimum grid voltages in each phase, to compute unbalanced voltage using Equation 8, as well as voltage THD of three phase grid on PCC bus without, with single tuned filter, and with double tuned filter respectively. By using the same procedure and equation, then obtained unbalance current and current THD. Table 2 represents unbalanced voltage and average voltage harmonics (THD_V) in three PV generator integration model to a three phase grid and four levels of irradiance with five different temperature levels. Table 3 shows the unbalanced current and average harmonic current (THD_I) on the PCC bus under the same condition.

Table 2. Unbalance Voltage and Average Voltage Harmonics

No.	Irradiance Level (W/m^2)	Temp (^0C)	Maximum Voltage (V) A	B	C	Unbalance Voltage (%)	THD_V (%) A	B	C	Average THD_V (%)
					Without Filter					
1.	400	20	308	308	308	0	2.66	2.51	2.59	2.59
		25	308	308	308	0	2.62	2.56	2.56	2.58
		30	308	308	308	0	2.69	2.60	2.63	2.64
		35	310	310	310	0	2.67	2.53	2.59	2.60
		40	310	310	310	0	2.68	2.58	2.62	2.62
2.	600	20	308	308	308	0	3.59	3.60	3.63	3.61
		25	308	308	308	0	3.70	3.64	3.61	3.65
		30	308	308	308	0	3.61	3.55	3.49	3.55
		35	310	310	310	0	3.66	3.56	3.55	3.59
		40	310	310	310	0	3.66	3.60	3.54	3.60
3.	800	20	310	310	310	0	4.16	4.19	4.06	4.14

No.	Irradiance Level (W/m2)	Temp (^{0}C)	Maximum Voltage (V) A	B	C	Unbalance Voltage (%)	THDV (%) A	B	C	Average THD_V (%)
					Without Filter					
		25	310	310	310	0	4.21	4.21	4.12	4.18
		30	310	310	310	0	4.12	4.14	3.99	4.11
		35	310	310	310	0	4.16	4.14	4.06	4.12
		40	310	310	310	0	4.11	4.14	4.03	4.10
4.	1000	20	310	310	310	0	4.12	4.08	4.01	4.07
		25	310	310	310	0	4.15	4.07	3.98	4.06
		30	310	310	310	0	4.04	3.99	3.93	3.98
		35	310	310	310	0	4.03	3.94	3.90	3.96
		40	310	310	310	0	4.03	3.90	3.90	3.94
					With Single Tuned Filter					
1.	400	20	308	308	308	0	0.22	0.23	0.22	0.22
		25	308	308	308	0	0.22	0.23	0.23	0.23
		30	308	308	308	0	0.23	0.23	0.22	0.23
		35	310	310	310	0	0.23	0.23	0.23	0.23
		40	310	310	310	0	0.23	0.23	0.23	0.23
2.	600	20	308	308	308	0	0.33	0.33	0.34	0.33
		25	308	308	308	0	0.34	0.34	0.34	0.34
		30	308	308	308	0	0.34	0.34	0.34	0.34
		35	310	310	310	0	0.34	0.33	0.34	0.34
		40	310	310	310	0	0.35	0.34	0.35	0.35
3.	800	20	308	308	308	0	0.42	0.43	0.43	0.43
		25	308	308	308	0	0.43	0.43	0.43	0.43
		30	308	308	308	0	0.43	0.41	0.43	0.42
		35	310	310	310	0	0.42	0.42	0.42	0.42
		40	310	310	310	0	0.43	0.42	0.43	0.43
4.	1000	20	310	310	310	0	0.43	0.43	0.43	0.43
		25	310	310	310	0	0.41	0.42	0.43	0.42
		30	310	310	310	0	0.42	0.42	0.42	0.42
		35	310	310	310	0	0.41	0.42	0.42	0.42
		40	310	310	310	0	0.41	0.42	0.42	0.42
					With Double Tuned Filter					
1.	400	20	307.8	307.8	307.8	0	0.09	0.09	0.10	0.09
		25	307.8	307.8	307.8	0	0.10	0.09	0.10	0.10
		30	307.8	307.8	307.8	0	0.10	0.09	0.10	0.10
		35	307.8	307.8	307.8	0	0.09	0.09	0.10	0.09
		40	307.8	307.8	307.8	0	0.09	0.09	0.10	0.09
2.	600	20	307.8	307.8	307.8	0	0.14	0.13	0.15	0.14
		25	307.8	307.8	307.8	0	0.15	0.13	0.15	0.14
		30	307.8	307.8	307.8	0	0.15	0.13	0.15	0.14
		35	307.8	307.8	307.8	0	0.15	0.13	0.15	0.14
		40	307.8	307.8	307.8	0	0.15	0.13	0.15	0.14
3.	800	20	307.8	307.8	307.8	0	0.19	0.17	0.19	0.18
		25	307.8	307.8	307.8	0	0.18	0.17	0.19	0.18
		30	307.8	307.8	307.8	0	0.18	0.16	0.18	0.17
		35	307.8	307.8	307.8	0	0.18	0.16	0.19	0.18
		40	307.8	307.8	307.8	0	0.18	0.16	0.18	0.17
4.	1000	20	307.8	307.8	307.8	0	0.18	0.17	0.19	0.18
		25	307.8	307.8	307.8	0	0.18	0.17	0.19	0.18
		30	307.8	307.8	307.8	0	0.18	0.17	0.19	0.18
		35	307.8	307.8	307.8	0	0.18	0.16	0.18	0.17
		40	307.8	307.8	307.8	0	0.18	0.17	0.18	0.18

Table 3. Unbalance Current and Average Current Harmonics

No.	Irradiance Level (W/m^2)	Temp (^{0}C)	Maximum Current (A) A	B	C	Unbalance Current (%)	THD_I (%) A	B	C	Average THD_I(%)
					Without Filter					
1.	400	20	9.8	12.5	10	16.10	2.01	1.27	1.69	1.657
		25	9.8	12.5	10	16.10	2.02	1.26	1.68	1.654
		30	9.8	12.5	10	16.10	2.01	1.27	1.68	1.653
		35	9.8	12.5	10	16.10	2.02	1.27	1.70	1.663
		40	9.8	12.5	10	16.10	2.02	1.27	1.70	1.663
2.	600	20	9.8	12.5	10	16.10	2.28	1.47	1.93	1.893
		25	9.8	12.5	10	16.10	2.03	1.15	1.93	1.704
		30	9.8	12.5	10	16.10	2.01	1.27	1.68	1.653
		35	9.8	12.5	10	16.10	2.02	1.27	1.70	1.663
		40	9.8	12.5	10	16.10	2.02	1.27	1.70	1.663
3	800	20	9.8	12.5	10	16.10	2.29	1.57	1.95	1.937
		25	9.8	12.5	10	16.10	2.30	1.56	1.95	1.936
		30	9.8	12.5	10	16.10	2.29	1.55	1.95	1.930

No.	Irradiance Level (W/m^2)	Temp (^{0}C)	Maximum Current (A) A	B	C	Unbalance Current (%)	THD$_I$ (%) A	B	C	Average THD$_I$(%)
			Without Filter							
		35	9.8	12.5	10	16.10	2.29	1.55	1.95	1.930
		40	9.8	12.5	10	16.10	2.29	1.55	1.93	1.923
4.	1000	20	9.8	12.5	10	16.10	2.36	1.63	1.88	1.957
		25	9.8	12.5	10	16.10	2.16	1.30	2.01	1.824
		30	9.8	12.5	10	16.10	2.34	1.63	1.87	1.947
		35	9.8	12.5	10	16.10	2.32	1.62	1.86	1.933
		40	9.8	12.5	10	16.10	2.32	1.61	1.83	1.920
			With Single Tuned Filter							
1.	400	20	10.45	10.45	10.45	0	0.09	0.09	0.09	0.09
		25	10.45	10.45	10.45	0	0.09	0.09	0.09	0.09
		30	10.45	10.45	10.45	0	0.09	0.09	0.09	0.09
		35	10.45	10.45	10.45	0	0.09	0.09	0.09	0.09
		40	10.45	10.45	10.45	0	0.09	0.09	0.09	0.09
2.	600	20	10.45	10.45	10.45	0	0.13	0.13	0.13	0.13
		25	10.45	10.45	10.45	0	0.13	0.13	0.13	0.13
		30	10.45	10.45	10.45	0	0.13	0.13	0.13	0.13
		35	10.45	10.45	10.45	0	0.13	0.13	0.13	0.13
		40	10.45	10.45	10.45	0	0.13	0.13	0.13	0.13
3.	800	20	10.45	10.45	10.45	0	0.17	0.17	0.17	0.17
		25	10.45	10.45	10.45	0	0.17	0.17	0.16	0.17
		30	10.45	10.45	10.45	0	0.17	0.17	0.17	0.17
		35	10.45	10.45	10.45	0	0.17	0.17	0.16	0.17
		40	10.45	10.45	10.45	0	0.17	0.16	0.16	0.16
4.	1000	20	10.45	10.45	10.45	0	0.17	0.17	0.17	0.17
		25	10.45	10.45	10.45	0	0.17	0.17	0.17	0.17
		30	10.45	10.45	10.45	0	0.16	0.16	0.16	0.16
		35	10.45	10.45	10.45	0	0.16	0.16	0.16	0.16
		40	10.45	10.45	10.45	0	0.16	0.16	0.16	0.16
			With Double Tuned Filter							
1.	400	20	10.44	10.44	10.44	0	0.03	0.02	0.03	0.03
		25	10.44	10.44	10.44	0	0.03	0.02	0.03	0.03
		30	10.44	10.44	10.44	0	0.03	0.02	0.03	0.03
		35	10.44	10.44	10.44	0	0.03	0.02	0.03	0.03
		40	10.44	10.44	10.44	0	0.03	0.02	0.03	0.03
2	600	20	10.44	10.44	10.44	0	0.04	0.03	0.04	0.04
		25	10.44	10.44	10.44	0	0.04	0.03	0.05	0.04
		30	10.44	10.44	10.44	0	0.04	0.03	0.04	0.04
		35	10.44	10.44	10.44	0	0.04	0.03	0.04	0.04
		40	10.44	10.44	10.44	0	0.04	0.03	0.04	0.04
3	800	20	10.44	10.44	10.44	0	0.05	0.04	0.05	0.05
		25	10.44	10.44	10.44	0	0.05	0.04	0.05	0.05
		30	10.44	10.44	10.44	0	0.05	0.04	0.05	0.05
		35	10.44	10.44	10.44	0	0.05	0.04	0.06	0.05
		40	10.44	10.44	10.44	0	0.05	0.04	0.05	0.05
4	1000	20	10.44	10.44	10.44	0	0.05	0.04	0.06	0.05
		25	10.44	10.44	10.44	0	0.05	0.04	0.06	0.05
		30	10.44	10.44	10.44	0	0.05	0.04	0.06	0.05
		35	10.44	10.44	10.44	0	0.05	0.04	0.06	0.05
		40	10.44	10.44	10.44	0	0.05	0.04	0.05	0.05

Figure 5 shows a grid voltage waveform of PV generator model connected three phase grid on two levels of solar irradiance (600 W/m^2 and 1000 W/m^2) on PCC bus without filter, with single tuned filter, and double tuned filter.

Figure 6 shows harmonics spectra of grid voltage of PV generator model connected three phase grid on two levels of solar irradiance (600 W/m^2 and 1000 W/m^2) on PCC bus without filter, with single tuned filter, and with double tuned filter.

Figure 7 shows performance of voltage and current average harmonics in three PV generator model connected three phase grids on PCC bus at four levels of irradiance (temperature 25^0 C), without filter, with single tuned filter, and with double tuned filter.

Table 3 shows that maximum voltages (phase A, B, and C), the system without filter for all irradiance levels (400 to 1000 W/m^2) and temperatures (20 to 40^{0}C) are stable at 308 and 310 volt, so it generates an unbalanced voltage of 0%. The maximum phase voltage of system using a single tuned filter for all irradiance levels and temperatures (20^{0}C, 25^{0}C, and 30^{0}C) is equal to 308 volt and at temperatures (35^{0}C and 40^{0}C), the value increases to 310 volt, resulting in same an unbalance voltage of 0%. The same value using a double tuned filter at all radiation levels (400 to 1000 W/m^2) and temperature (20^{0}C to 40^{0}C) is equal to 307.8 volt, resulting in same an unbalanced voltage of 0%. Under the condition without filter, irradiance level remains, and temperature increases, average voltage harmonics (THD_V) is relatively the same. While for the condition without filter and fixed temperature, but irradiance level increases, then average voltage harmonics also increases. The lowest average voltage harmonics is generated at irradiance of 400 W/m^2 and temperature of 25^{0}C as 2.58%, while the highest occurs at irradiance of 800 W/m^2 and temperature of 25^{0}C as 4.18%. Under the condition of using single tuned filter, irradiance remains, and temperature increases, then average voltage harmonics is relative same. Under the condition of without filter, fixed temperature, but irradiance increase, then average voltage harmonics also increases. The lowest average voltage harmonics is generated at irradiance 400 W/m^2 and temperature 20^{0}C as 0.22%, while the highest harmonics occurs at irradiance of 800 W/m^2 and temperature of 25^{0}C as 0.43%. Application of double tuned filter at fixed irradiance and increased temperature produces relatively same average voltage harmonics. On the other hand, at constant temperature and irradiance, so that average voltage harmonics increases. The lowest average voltage harmonics is generated at irradiance of 400 W/m^2 and temperature of 20^{0}C as 0.09%, while the highest occurs at irradiance of 1000 W/m^2 and temperature of 25^{0}C as 0.18%. The use of double tuned filter can suppress 11th and 13th harmonics so as significantly reduce average voltage harmonics, compared to single tuned filter that only reduce 5th harmonics.

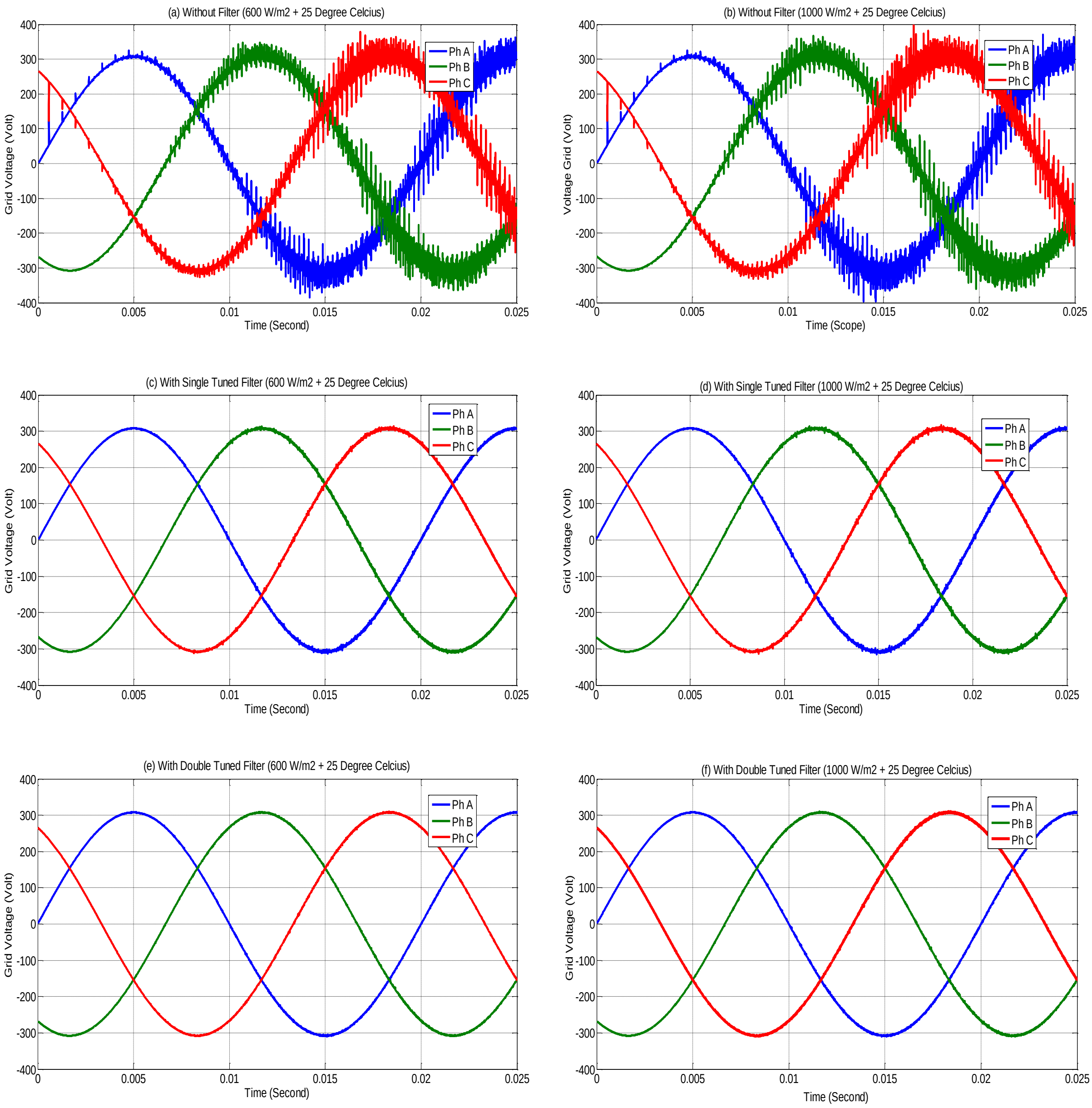
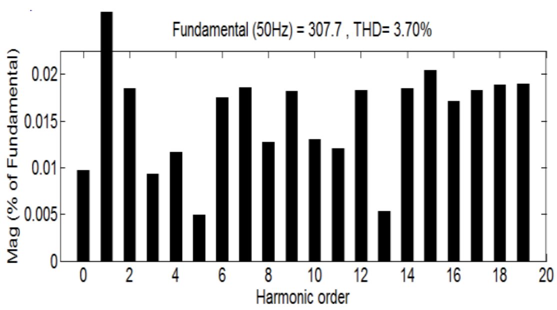
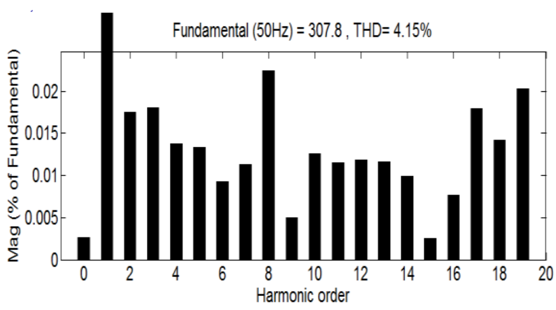


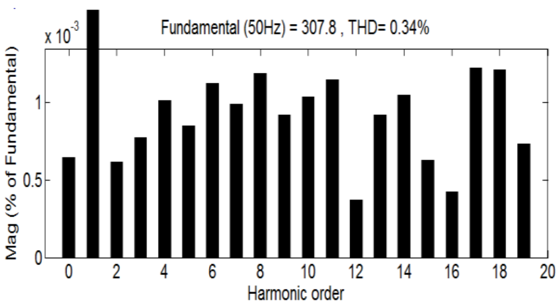
Figure 5. Voltage waveform at two levels of solar irradiance with temperature of 25^0 C



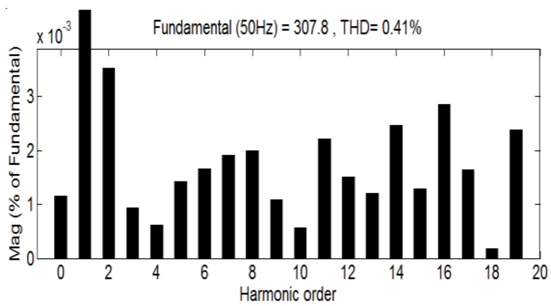
(a) Without filter (irradiance 600 W/m^2)



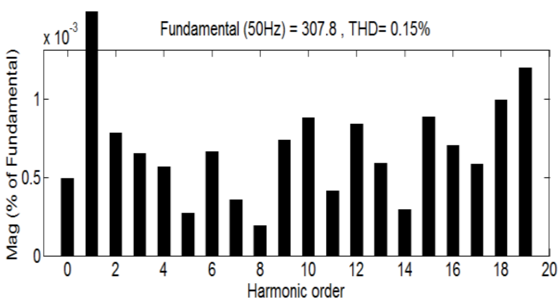
(b) Without filter (irradiance 1000 W/m^2)



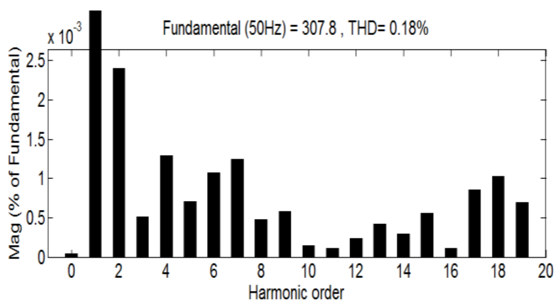
(c) With single tuned filter (irradiance 600 W/m^2)



(d) With single tuned filter (irradiance 1000 W/m^2)



(e) With double tuned filter (irradiance 600 W/m^2)



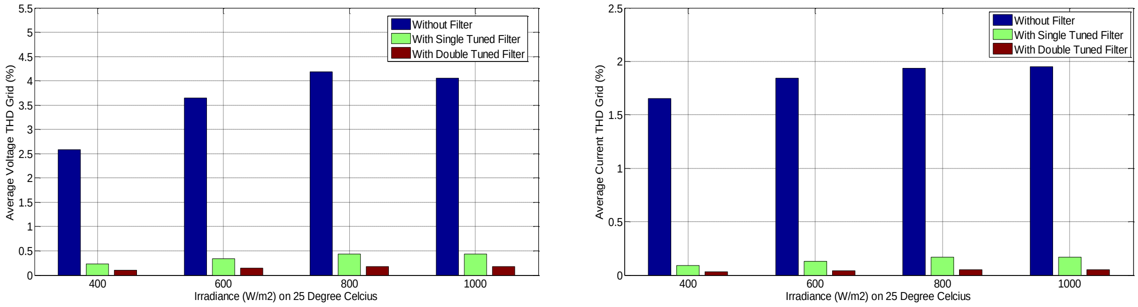
(f) With double tuned filter (irradiance 1000 W/m^2)

Figure 6. Voltage harmonics spectra on phase A at two levels of solar irradiance with temperature of 25^0 C

Table 3 shows that maximum currents in phase A, B, and C, for system without filter for all irradiance levels (400 to1000 W/m^2) and temperatures (20 to 40^0C) are different e.i. 12.5, 9.8, and 10 A respectively, resulting in an unbalanced current of 16.10%. In the same condition, single tuned filter is able to balance phase currents of 10.45 ampere each, resulting in an unbalanced current equal to 0%. Under without filter conditions, irradiance remains, and temperature increases (20^0C to 40^0C), average current harmonics (THD_I) is relatively same. While the conditions without filter and temperature remains, but irradiance increases, then average current also increases. The lowest average current harmonics generated at irradiance of 40^0 W/m^2 and temperature of 300C as 1.653%, while the highest occurs at irradiance of 1000 W/m^2 and temperature of 20^0C as 1.957%. Under condition of with single tuned filter, fixed irradiance, and temperature increases, then average current harmonics is relatively same. Under same filter condition and fixed temperature, but irradiance increases, so average current harmonics value also increases. The lowest average current harmonics is generated at 400 W/m^2 irradiance and temperature (20^0C to 40^0C) as 0.09%, while the highest happens at irradiance of 800 W/m^2 and temperature (20^0C to 35^0C) as 0.17%. The application of double tuned filter at fixed irradiation and temperature increase produces a relatively constant current harmonics. Otherwise, on fixed temperature and irradiance increases, then average current harmonics also increases. The lowest average current harmonics is generated at irradiation of 400 W/m^2 and temperature (20^0C to 40^0C) as 0.03%, while the highest harmonics hanppen at irradiance of 800 W/m^2 and temperature

(20^0C to 40^0C) as 0.05%. Implementation of double tuned filter on three phase PV generator can decrease average current harmonics better than single tuned filters.

Figure 7(a) shows that at increasing irradiance level (400 W/m^2 to 1000 W/m^2) and fixed temperature (25^0 C), average voltage harmonics also increases. Double tuned filter can significantly reduce average voltage harmonics of system compared to single tuned filter and without filter. Figure 7(b) also shows that at increasing irradiance level (400 W/m^2 to 1000 W/m^2) and fixed temperature (25^0 C), average current harmonics also increases. Double tuned filter is mostly effective to suppress 11^{th} and 13^{th} harmonics so it can migitate both average voltage harmonics and average current harmonics, better than system with single tuned filter which can only decrease 5^{th} harmonics.



(a) Average voltage harmonics (b) Average current harmonics

Figure 7. Performance of average harmonics at four irradiance levels (temperature 25^0C)

4. CONCLUSION

Multi units of PV generator connected to a three phase distribution network, without filter, with single tuned, and with double tuned filter at all temperatures and irradiance levels results in relatively stable phase voltage (308 volt and 310 volt), so able to generate an unbalanced voltage of 0%. The maximum phase current for the system without filter at all temperatures and radiation levels of 12.5, 9.8, and 10 A, respectively, resulting in an unbalanced current of 16.10%. Under the same condition, single tuned and double tuned filters are able to balance phase current to 10.45 A and 10.44 ampere respectively, resulting in an unbalanced current of 0%. Implementation of single tuned and double tuned filters able to reduce unbalance current according to ANSI/IEEE 241-1990. At constant temperature and irradiance increases, both average voltage and current harmonics also increase. Double tuned active filter is the most effective to suppress the 11^{th} and 13^{th} harmonics so capable to migitate average voltage and current harmonics better than system using single tuned filter which can only reduce 5^{th} harmonic within IEEE 519-1992.

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